UTILISING CLEAN COAL TECHNOLOGIES FOR MEETING NIGERIA'S ENERGY NEEDS

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Abstract
Coal is expected to remain one of the dominant fuels in global electricity power generation as a result of its low cost, high reliability and high availability. In Nigeria, however, coal is yet to make a significant contribution to Nigeria's energy needs because of the numerous challenges associated with coal electricity power generation. One of the challenges is that the use of coal to generate electric power produces toxic gases which are hazardous to human health and the environment; it is also perceived as dirty to the environment. This paper focuses on the roles clean coal technologies can play in the sustainable exploitation of Nigeria's coal reserves and how it can be effectively utilized to meet Nigeria's energy needs. The Nigerian situation on electricity is reviewed, and the Nigerian national policy on coal utilization is evaluated. Recommendations on methods for implementing some aspects of the Nigerian national coal policy are made. Many clean coal technologies that can help overcome the challenges of electric power generation were also reviewed. It is concluded that the core of the Nigerian national policy on coal should be the promotion of clean coal technology for electricity production. Clean coal technologies can reduce the hazardous gaseous emissions generated by the thermal decomposition of the fuel. By developing clean coal technologies, Nigeria will be able to use her considerable coal resources better and reduce the emissions of harmful substances associated with coal mining, thereby make a significant contribution to Nigeria's energy needs.

1.0 INTRODUCTION

1.1 Origin of Coal

Coal is a brownish-black sedimentary rock usually occurring in rock strata in layers or veins called coal beds or coal seams. Coal is the solid end-product of millions of years of decomposition of organic materials. Over millions of years, accumulated plant and animal matter is covered by sediment and stored within the earth's crust, gradually being transformed into hard black solids by the sheer weight of the earth's surface. Coal, like other fossil fuel supplies, takes millions of years to create but releases its stored energy within only a few moments when burned. Different types of coal exist, and they all have different uses. However, the most significant uses of coal are in electricity generation, steel production, cement manufacturing and as a liquid fuel. (WCA, 2016)

1.2 Types of Coal

Coal is a complex resource and can vary in composition even within the same deposit. There are four different types or ranking levels of coal, lignite, sub-bituminous coal, bituminous coal, and anthracite. Each type with differences in energy output as a result of increased pressurization, heat, and time. The four types of coal are discussed extensively in literature (Parr, 1922; World Coal Institute, 2005).

1.3 Reserves of Coal

Over 984 billion tonnes of proven coal reserves are estimated worldwide (World Coal Institute, 2005). The implication is that there are enough coal reserves to last us for over 190 years. Coal can be found on every continent in over 70 countries, with the biggest reserves in the USA, Russia, China and India (World Coal Institute, 2005). Nigeria ranks low in worldwide coal production, with less than 10 thousand tons of coal production yearly (Statistical Review of World Energy 2015). Nigerian Coal Corporation (NCC) estimated Nigeria's coal reserves to be at least 2 billion tons, with approximately 190 million metric tons as proven (Odesola *et al.*, 2013). Although coal was the first energy resource to be exploited by Nigeria, Coal production has dropped to insignificant levels from its high of almost 1 million tonnes in 1959 Fig. 1 (Odesola *et al.*, 2013).

Nigeria is endowed with abundant sub-bituminous coal resources distributed in about 22 coal fields spread over the country. Fig. 2 presents the map showing the location of the coals in the sedimentary basins of Nigeria (Nyakuma, 2015; Obaje, 2009). Coal seams occur in three main stratigraphic levels (Ogunsola, 2008):

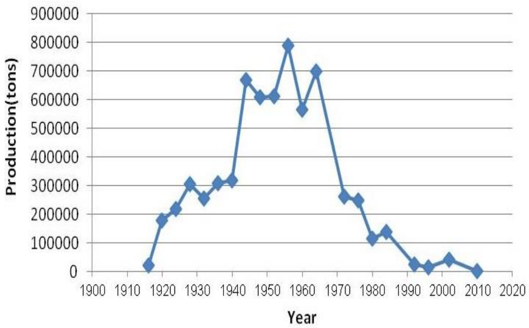

Fig. 1: Nigerian Coal Production Since 1909 (Odesola *et al.*, 2013)

1. The brown coals (lignite) of Ogwashi-Asaba Formation of Miocene to Pliocene ages,
2. The upper and lower sub-bituminous coal measures of Maastrichtian age and
3. The bituminous coals of the Awgu shales of Coniacian age.

Table 1 provides an overview of estimates and proven reserves in some coal mines in Nigeria. More comprehensive information is given in the Nigeria-Summary of Coal Industry document (M2M Workshop – Nigeria, 2005).

The coals in the coal mines are low in sulfur and ash content, making them attractive for use as a source of fuel for electric power generation. Table 2 presents the ultimate analyses of coal from Afuze coalfields in Afuze, Edo state; Shankodi-Jangwa coal seam in Obi, Nasarawa state; and the Garin Maiganga coal mines in Akko, Gombe state of Nigeria (Nyakuma, 2015). Proximate analyses of the coal from the three selected coal fields are also presented in Table 3 (Nyakuma, 2015). The low moisture content of the coal in all three fields indicates the maturity of coal found in Nigeria.

Table 1: Nigeria's Coal Mines (M2M Workshop – Nigeria, 2005)

Mines	Coal Type	Estimated Reserves (Million Tons)	Proven Reserves (Million Tons)	Depth of Coal (m)
Okapara	Sub-Bituminous	100	24	180
Onyeama	Sub-Bituminous	150	40	N/A
Ihioma	Lignite	40	N/A	20-80
Ogboyoga	Sub-Bituminous	427	107	20-100
Ogwashi Azagba /Obomkpa	Lignite	250	63	15-100
Ezimo	Sub-Bituminous	135	56	30-45

Table 2: Ultimate Analyses of Coals from Selected Nigerian Coal Fields (Nyakuma, 2015)

Property	Garin Maiganga Coal Mines	Shankodi-Jangwa Coal Seam	Afuze Coalfields
Carbon	61.69%	71.46%	72.46%
Hydrogen	4.42%	6.40%	6.07%
Nitrogen	1.07%	1.37%	1.63%
Sulphur	0.39%	2.03%	1.41%
Oxygen	32.16%	18.76%	18.43%
Heating Value	23.7MJ/Kg	27.34 MJ/Kg	30.52 MJ/Kg

Table 3: Proximate Analyses of Coals from Selected Nigerian Coal Fields (Nyakuma, 2015)

Property	Garin Maiganga Coal Mines	Shankodi-Jangwa Coal Seam	Afuze Coalfields
Moisture	5.28%	5.14%	1.97%
Volatile Matter	51.16%	40.73%	45.80%
Ash	21.05%	14.94%	30.99%
Fixed Carbon	22.52%	39.18%	21.24%
Mineral Matter	22.95%	17.25%	34.24%

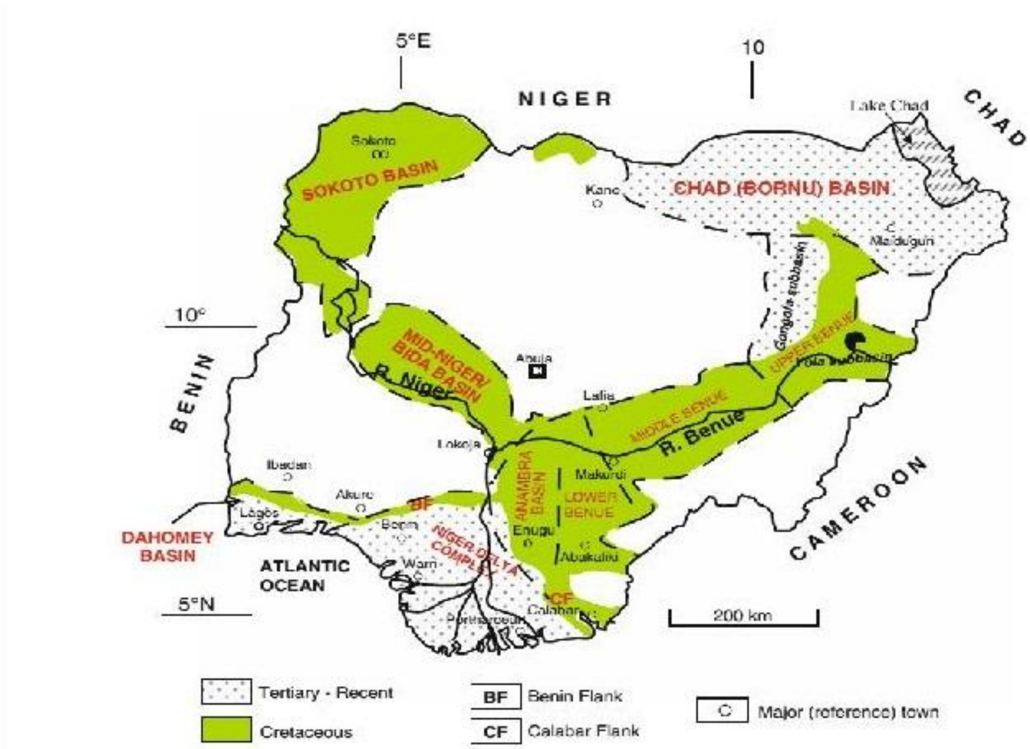

Fig. 2: Nigeria's Sedimentary Coal Basins And Deposits (Obaje, 2009)

2.0 ELECTRICITY FROM COAL

2.1 Coal and Electricity

In this day and age, electricity is an essential part of our lives and economy. Coal plays a vital role in electric power generation worldwide. Coal-fired electric power plants currently fuel 41% (Fig. 3) of global electricity (WCA, 2016). In some countries, coal fuel produces a high percentage of electric power generated. Table 4 presents the percentage of coal used for electric power generation in different countries.

Table 4: Coal in Electricity Generation (IEA, 2010)

South Africa 93%	Poland 92%	PR China 79%
Australia 77%	Kazakhstan 70%	India 69%
Israel 63%	Czech Rep 60%	Morocco 55%
Greece 52%	USA 49%	Germany 46%

Table 4 indicates that coal is an important electric energy source for many countries, such as South Africa, Poland, People Republic of China, etc. The importance of coal to electricity generation worldwide is set to continue. Sasol Limited, an integrated energy, and chemical company, operates commercial clean coal gasification plants in Secunda, Mpumalanga, South Africa, and in Sasolburg, Free State province of South Africa to generate electricity (Sichinga and Buchanan, 2005). Sub-Bituminous grade coal is used in these plants. Nigerian coal being sub-bituminous can use this same technology in generating electric power.

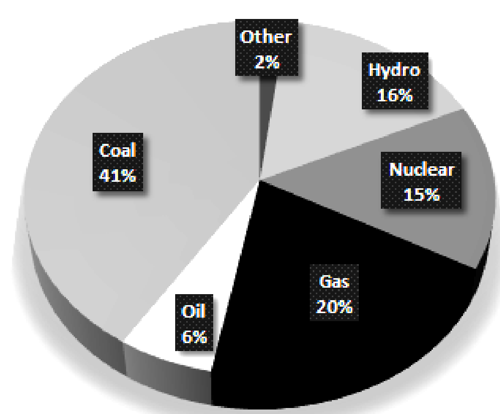

Fig. 3: Total World Electricity Generation by Fuel (WCA, 2016)

2.2 Conversion of Coal to Electricity

The process of converting coal to electricity involves the milling of the coal to a fine powder, and its combustion in a boiler to generate steam to drive turbines (IEA, 2010). A diagram of the process is shown in Fig. 4 below.

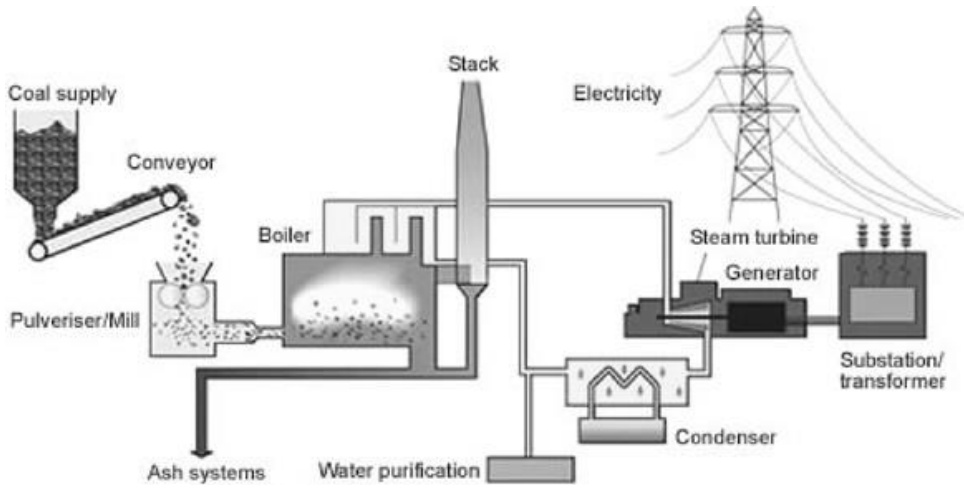

Fig. 4: Conversion of Coal to Electricity (Conventional PCC) (Moazzem *et al*., 2012)

The combustion process in the boiler generates gaseous emissions by the thermal decomposition of the coal. These gases include sulphur dioxide SO_2, nitrogen oxides (NO_2), carbon dioxide (CO_2), mercury, and other chemical by-products that vary depending on the type of the coal being used (Moretti and Jones, 2012). These emissions have been established to have a negative impact on the environment and human health, contributing to acid rain, lung cancer, and cardiovascular diseases.

2.3 Generation and Distribution of Electricity in Nigeria

Nigeria's electric power generation and grid distribution capability is currently in the range of 3,500 to 4,500 megawatts (MW) (MMSD, 2010). This is far short of that required to support the current population and to keep the economy growing. Current estimates of National electricity demand are in the range of 20,000 to 25,000 MW. Power is currently produced from several gas-fired and hydropower generating facilities. Power from the electricity distribution grid is supplemented by numerous small, costly diesel powered generators in the country's cities, towns, and villages. The electricity supply in Nigeria is characterized by frequent power failures and load shedding, resulting in economic losses through lost production, damaged equipment and the need for expensive stand-by power. The Country has an over reliance on its current non-coal generating facilities while its vast coal reserves remain unutilized.

Privatization of the energy sector has already been initiated through the Electric Power Sector Reform Act of 2005 (NERC, 2005). The former Nigerian National Electricity Power Authority (NEPA) has been unbundled into generation, transmission and distribution companies that have become privatized. Meanwhile, several Independent Power Producers (IPPs) are already in operation. The exploitation of coal for electricity generation and the production of coal briquettes for domestic and industrial heating will bring a number of benefits including the following:

i. Increased and more reliable electricity supply,
ii. Lower cost electrical energy,
iii. Expanded industrialization of the economy,
iv. Increased employment and human resources development,
v. Increased capacity utilization of existing industries and
vi. Increased national income through taxes

3.0 NATIONAL ENERGY POLICY ON COAL

Clean Coal Technologies are environmentally superior and more operationally efficient than technologies in common use today. Improved operating efficiencies of new power generation technologies from the Clean Coal Technology programs are 30-40% higher than conventional coal plants. This translates to nearly the same percentage reduction in carbon dioxide emissions.

A cornerstone of the National Policy on Coal is the promotion of clean coal for electricity production. The following objectives of the National Energy Policy seek to promote the utilization of clean coal. These include: (Lukman, 2003)

i. Promotion of production of coal for export.
ii. Promotion of effective utilization of coal for complementing the nation's energy needs and as an industrial feedstock.
iii. Attracting increased investment into, and promote indigenous participation in the coal industry.
iv. Utilizing coal to meet the critical national need of providing a viable alternative to fuel wood in order to conserve our forests.
v. Minimizing environmental pollution arising from the utilization of coal.

To achieve these stated objectives, the National Policy has adopted the following strategies: (Lukman, 2003)

i. Intensifying the drive for coal exploration and production activities.
ii. Providing adequate incentives to indigenous and foreign entrepreneurs so as to attract investments in coal exploration and production.
iii. Providing adequate incentives for the large scale production of **coal stoves** at affordable prices.
iv. Providing adequate incentives to indigenous and foreign entrepreneurs for the establishment of coal-based industries.
v. Developing adequate infrastructure for handling and transportation of coal within and out of the country.
vi. Organizing awareness programs for the use of smokeless coal briquettes as an alternative to fuel wood.
vii. Encouraging R & D in the production, processing and utilization of coal.
viii. Introducing clean coal technologies into coal utilization.
ix. Re-introducing the use of coal for power generation
x. Focus on Clean Coal Technologies to provide cleaner electric power at less cost.

4.0 CLEAN COAL TECHNOLOGIES

Clean coal technology is a term used to describe the combination of different technologies to generate electricity from coal with minimal environmental impacts. In practice 'clean coal' technology means a range of technologies which includes the preparation of coal (i.e. washing), its combustion, and the clean-up of waste gases (e.g. CO_2, SO_2, NOx) as well as the better maintenance and management of facilities and the use of more sophisticated control and monitoring systems (Watson and Oldham, 1999). In the past, the methods used for cleaning coal included chemically washing impurities from coal, gasification, flue gas treatment, carbon capture, and storage technologies; to capture CO_2 from flue gas and dewatering low calorific coals to increase their energy conversion rates, and thus the efficiency of electricity generation. However, modern methods have been developed, and they include Efficiency improvement/Advanced Combustion Technologies, Integrated Carbon Capture and Sequestration Technology (CSS), Underground Coal Gasification, Oxy-fuel Combustion Carbon Capture Technology and Integrated Gasification Combined Cycle Process.

4.1 Advanced Combustion Technologies

Advanced Combustion Technologies are developed to incorporate new techniques and components with the old infrastructure to make power generation from coal cleaner, efficient and effective while reducing costs of production. These combustion technologies are amenable to CO_2 sequestration (by producing high pressure and/or high CO_2 flue gas concentration (Beèr, 2000). Some of these technologies are Low Emission Boiler Systems (LEBS) (Moretti and Jones, 2012), Indirectly Fired Power System (IFPS), and Fluidized Bed Combustion (Philibert and Podkanski, 2005).

4.1.1 Low Emission Boiler Systems (LEBS)

Low Emission Boiler Systems are the future of coal-fired power plants. These plants rates of emissions of SOx, NOx, and particulates are much lower than those of the other coal-fired power plants, and the net efficiency of these systems is also higher than that of coal-fired utility plants. Fly ash and scrubber solids waste streams are produced from these systems which make them very clean and efficient in nature. The ash is easily transformed into a non-leachable slag, which can be used for blasting or roofing granules. The slag byproduct can be used for making cement and other building materials. This gives the Low Emission boiler system a dual role that help saves energy and cost (Moretti and Jones, 2012).

4.1.2 Indirectly Fired Power System (IFPS)

Indirectly Fired Power System uses an indirectly fired gas turbine combined cycle, where heat energy is supplied to the gas turbine through series of high-temperature heat exchangers (Zhu, 2015). In the indirectly fired cycle, the products obtained during combustion are shielded from the gas turbine, and a higher thermal efficiency is also produced. Indirectly Fired Power System use compressed air, and other fuels such as natural gas can be used to increase the temperature in the air furnace to that of the gas turbine inlet. Indirectly Fired Power System reduces the emission of SO_2 and NO_X significantly. This combustion technique is very promising however, reducing carbon emissions to its lowest for a coal fired boiler, and producing electricity that will cost at a cheaper rate than today's power plants.

4.1.3 Fluidized Bed Combustion

Fluidized Bed Combustion systems provide an alternative form of using coal to generate electricity with minimal carbon emissions. Two types of Fluidized Bed Combustion are available: the atmospheric system and the pressurized system. In the atmospheric system, dolomite is used as a sorbent to capture sulfur and its compounds from coal combustion. A stream of air is used to suspend the sorbent and change it into a fluid-like substance. The pressurized bed combustion (Fig. 5) operates in the same way as the atmospheric system except that it runs at a higher pressure, which creates a gas stream at temperatures that can drive a steam turbine (Watson and Oldham, 1999).

In Japan, research and development of pressurized fluidized-bed combined electricity power generation technology was conducted at J-POWER's Wakamatsu Coal Utilization Research Center (now known as Wakamatsu Research Institute) using a 71 MWe-PFBC Plant (JCOAL, 2007). The test plant was the first plant in the world to adopt a full-scale ceramic tube filter (CTF) capable of collecting dust from high-temperature, high-pressure gas at a high-performance level. Results of PFBC technology development were (1) Gross efficiency of 43% was achieved by increasing efficiency through combined power generation utilizing pressurized fluidized-bed combustion and (2) SO_x level of approximately 5 ppm through in-bed desulfurization; NO_x level of approximately 100 ppm through low-temperature combustion (approximately 860ºC), and dust of less than 1mg/Nm^3 by CTF.

4.2 Integrated Gasification Combined Cycle (IGCC)

In integrated gasification combined cycle (IGCC) systems, steam and hot pressurized air or oxygen is mixed with coal in a reaction that forces carbon molecules to be separated (Subbarao, 2010). The produced syngas, which comprises carbon monoxide and hydrogen, is then cleaned and burned in a gas turbine to generate electricity. The heat energy from the gas turbine can also be used to power another steam turbine. Integrated Gasification Combined Cycle power plants generally produce two forms of energy and that makes the plants to have a potentially high fuel efficiency. In addition to that, if an improvement is made on the technology to allow rechanneling of waste heat back to the process steam, there will certainly be an increase in the conversion efficiency. The IGCC is relatively efficient and the byproducts generated from coal gasification have series of domestic and industrial uses.

A practical example of the IGCC plant is the Duke Energy's Edwardsport Generating Station in Knox County, Ind., United States. The plant started operation commercially in June 2013. The plant is one of the world's cleanest coal-fired power systems and is the first to use integrated gasification combined cycle (IGCC) system on a large scale. The 618MW advanced IGCC plant substantially reduces the acid gases emission and environmental impact of burning coal to generate electricity in a coal-fired power plant (Sourcewatch, 2106).

The Duke Energy's Edwardsport IGCC power plant gasifies Bituminous coal, strips out acid gases and other impurities, and then burns the produced cleaner gas to generate electricity (Sourcewatch, 2106). The IGCC power plant produces 10 times as much power as the former coal-fired power plant at Edwardsport, yet with about 70 percent fewer emissions of sulfur dioxide, nitrogen oxide and particulates combined together. The efficiency of the IGCC power plant also significantly reduces its carbon emissions per megawatt-hour by nearly half. As Nigerian power plant could be built using the IGCC technology as the grade of coal used in the Duke Energy's Edwardsport Generating Station is similar to the of Nigerian coal.

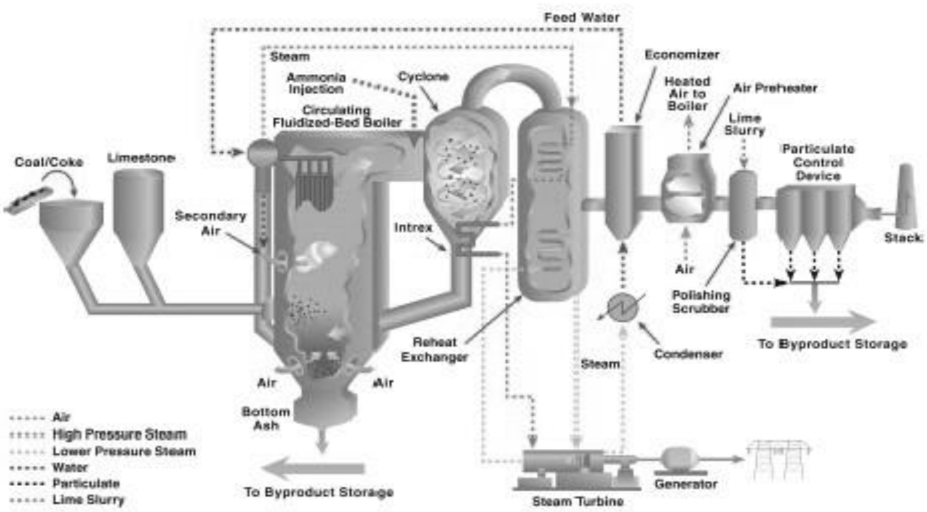

Fig. 5: Basic CFB Plant (Source JEA, 2003)

4.3 Integrated Carbon Capture and Sequestration Technology (CSS)

Carbon Capture and Sequestration (CCS) is a system that captures carbon dioxide from any available source, compresses it into a dense liquid-like substance, injects and permanently stores the CO_2 underground (Folger, 2013). Coal-fired plants in addition to power generation, generally release carbon dioxide into the atmosphere, which pollutes the environment. A better option is to sequester the carbon dioxide and prevent or slow its emission into the air. To achieve this, however, the CO_2 must first be captured (Beèr, 2000).

Integrated Carbon Capture and Sequestration Technology is a post-combustion capture process that captures carbon dioxide from the byproduct of combustion using sorbents, solvents or membrane separation to remove the produced CO_2 from the byproduct. The captured CO_2 can be pipelined and used for enhanced oil recovery in depleting oil fields during crude oil production. The Carbon Capture and Sequestration Technology, (Beèr, 2000) consist of three major steps:

i. Capture: The produced CO_2 from byproducts of combustion processes is separated from the other gases.
ii. Transport: The captured carbon dioxide is then compressed and transported through pipelines, ships or other methods to a suitable site where it can be used or stored.
iii. Storage: The carbon dioxide is injected into deep rock formations for secondary oil recovery to increase the pressure available within the formation and the remaining stored permanently.

A practical example of Integrated Carbon Capture and Sequestration Technology is the Boundary Dam CSS Project. The project transformed the old Boundary Dam Power Station near Estevan, Saskatchewan, Canada into a reliable, long-term producer of up to 115 megawatts (MW) of baseload electricity, capable of reducing acid gas emissions significantly (Monea, 2013). The carbon dioxide produced is also captured. The captured CO_2 is sold and also transmitted through a pipeline to depleted oil fields in southern Saskatchewan for secondary oil recovery while the unused carbon dioxide is stored. In addition to capturing carbon dioxide, the CSS plant also captures and sells other byproducts during power generation. The sulphur dioxide in the byproduct is also captured and converted to useful sulphuric acid for industrial purposes. Fly ash, another byproduct is captured as well and used in the production of ready-mix concrete, pre-cast structures, and concrete products.

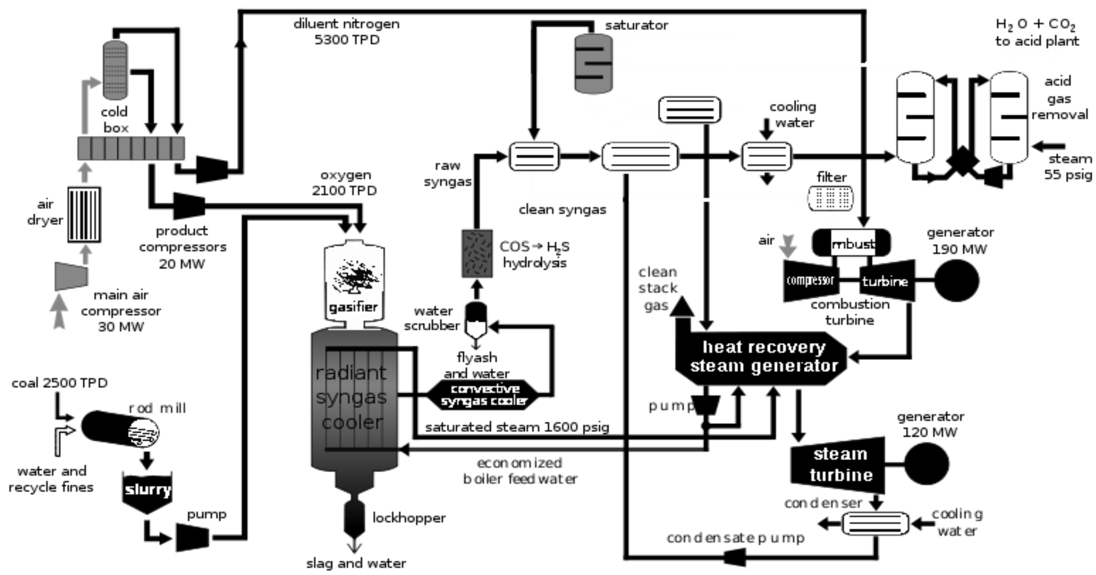

Fig. 6: **Schematic of Integrated Coal Gasification Combined Cycle Unit (Crook, 2006)**

4.4 Underground Coal Gasification

Underground Coal Gasification is a process of harvesting coal which is purer than the cleanest of current coal technologies. In this process, coal is gasified without mining. Two wells with a distance of twenty to fifty meters apart are drilled into the coal seam. Then, air is introduced through a pump into the injection well, while burning charcoal is placed into the production well. As the production well burns, it draws air from the bottom of the injection well and through the coal seam. This process makes the production well to burn and form a tunnel in the direction of the injection well. When the tunnel reaches the injection well, fire explodes and consumes every area surrounding the two wells and the tunnel. The resulting gas is captured and harvested (Watson and Oldham, 1999).

There are four basic problems associated with the UCG that have streamlined its development and delayed exploitation of its theoretical benefits: (Ali et al., 2012)

1. It is not economical when compared to standard methods for coal harvesting
2. The combustible gas generated is diluted with nitrogen due to air that is pumped into the coal seam for combustion
3. There is possibility of coal seam to collapse
4. And the UCG process can significantly contaminate underground water.

However, availability of cheaper oxygen will improve the viability of UCG. If oxygen is pumped into the injection wells instead of air, the resultant gas is not diluted with nitrogen, thereby increasing the productivity of UCG.

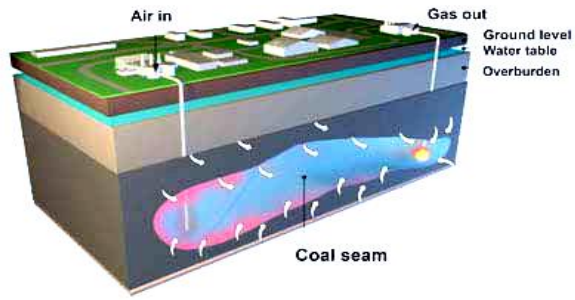

Fig. 7: Schematic of Underground Coal Gasification (Walter, 2007)

4.5 Oxy-fuel Combustion Carbon Capture Technology

In this process, oxygen needed for combustion is separated from air prior to combustion and the fuel is combusted in oxygen diluted with recycled flue-gas instead of using air. This oxygen-rich, nitrogen-free atmosphere results in final flue-gases consisting mainly of CO_2 and H_2O (water), so producing a more concentrated CO_2 stream for easier purification (Beèr, 2000).

This oxygen-rich, nitrogen-free atmosphere results in final flue-gases consisting mainly of CO_2 and H_2O (water), so producing a more concentrated CO_2 stream for easier purification. The Oxy-fuel Combustion technology has significant advantages over traditional air-fired plants.

Among these advantages are:

i. The mass and volume of the flue gas are significantly reduced.
ii. Because the flue gas volume is reduced, less heat is lost during combustion.
iii. The size of the flue gas treatment equipment is also significantly reduced.
iv. The flue gas is primarily CO_2 suitable for sequestration and storage.
v. Most of the flue gases are condensable; this makes compression separation possible.

Heat of condensation can be captured and reused rather than lost in the flue gas.

Oxy-fuel is an alternative to removing CO_2 from the flue gas from a conventional air-fired fossil fuel plant. However, an oxygen concentrator might be able to help, as it simply removes nitrogen from air.

5.0 CONCLUSIONS

Coal is expected to continue to be an important fuel for electric power generation due to its low cost and abundance. Conventional coal power generation is a major contributor to global greenhouse gas emissions through the production of acid gases and is increasingly being regulated. However, clean coal technologies that improve the environmental performance of coal electric power generation are expected to enable coal to remain an attractive fuel option well into the future. Different clean coal technologies that increase the efficiency of coal power plants and reduce emissions are being developed to meet these challenges. As a result of these advances and increasing emissions regulation around the world, the use and development of technologies that reduce SO_2, NOx, and particulate emissions have increased over the past decade. Concurrently, combustion technologies including super critical (SC), ultra-super critical (UC) pulverized coal combustion (PCC), and circulating and pressurized fluidized bed combustion (FBC) technologies are increasing the power conversion efficiencies of coal power plants. These advanced technologies have enabled simultaneous improvements in emissions and economics of coal-fired generation.

The greatest opportunity for the Nigerian coal industry lies in the deployment of the following three clean coal technologies which are Integrated Carbon Capture and Sequestration Technology, Oxy-fuel Combustion Carbon Capture Technology and Integrated Gasification Combined Cycle Process. These technologies capture carbon dioxide and other gaseous pollutants from coal power conversion processes and store it in either underground or in offshore geological formations; virtually eliminating greenhouse gas emissions from coal combustion.

The technologies are currently being used to solve global energy challenges and meet the vastly increasing energy demands. The selectivity of any of these technologies is based on the suitability of the system to be deployed and how it can be utilized effectively and efficiently to solve National energy challenges. Clean Coal Technologies can undoubtedly provide the platform to solve the energy challenges in Nigeria while minimizing the emission of harmful gaseous byproducts. This will enable Nigeria to utilize her vast coal resources to produce abundant electricity that will meet the energy needs of the nation.

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